

Functional demonstration of accelerometer-assisted beacon tracking

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ABSTRACT

NASA/JPL has been developing technologies to accurately point a laser beam from deep space with sub-micro-radian precision for data transmission systems. A novel approach to achieve this goal is based on using high bandwidth inertial sensors to compensate for jitter caused by spacecraft vibrations. The use of high bandwidth inertial sensors promises to enable the implementation of laser communication links anywhere within the solar system and beyond. A functional demonstration of closed-loop accelerometer-assisted beacon tracking under simulated spacecraft vibration was undertaken, in order to validate innovative concepts, technologies, sub-systems and algorithms that achieve the sub-micro-radian pointing accuracy necessary for optical communication systems from deep space. The laboratory demonstration included integration of the complete acquisition, tracking, and pointing system with inertial sensors (e.g. accelerometers). Double integration, bias and initial velocity estimation algorithms were developed, verified and implemented. Accelerometer performance was characterized and integrated to the system. A laser beacon was mounted on a platform that simulates spacecraft vibrations. Vibrations were introduced into the beacon and were simultaneously sampled by the accelerometer. These signals were used to close the pointing loop. Closed loop tracking of the vibrating beacon was achieved using the accelerometer information interlaced with a slow-rate reference update (laser beacon centroids). This presentation will describe the details of the functional demonstration of accelerometer-assisted beacon tracking and pointing in a laboratory environment under simulated spacecraft vibration.

Keywords: Acquisition, tracking and pointing, inertial sensors, accelerometer, free-space optical communications, deep space communications.

1. INTRODUCTION

NASA has been developing communication systems that enable affordable, virtual presence throughout the solar system by increasing volume and timeliness of space data transfer directly to users while minimizing the cost and the impact of communications systems on future spacecraft. One highly promising technology to achieve this goal is free-space optical communications. However, in order to enable this technology, an acquisition, tracking and pointing (ATP) architecture that is independent of range (to receiver system) needs to be developed. Furthermore, pointing error analysis (for a deep space link) has shown that S/C vibration is the dominant contributor to mis-pointing¹. Therefore, the ATP functions have to be demonstrated to clearly and effectively compensate for spacecraft (S/C) jitter in a simulated vibration environment. In this article, a novel architecture that is independent of range is validated and achievements of the steps towards a full sub-micro-radian pointing demonstration in a simulated vibration environment are presented.

The effect of spacecraft vibration upon the pointed optical signal is graphically shown in Figure 1. There is a large slow motion due to S/C dead-band excursion and a high frequency jitter due to vibrations. Generally two combined mechanisms are used to compensate for these motions. One is to determine the known motion and the second is to use a high sampling rate. The known motion is typically obtained by sampling a focal plane array (FPA) that has the receiver laser beacon imaged onto it. This can be done at a low sampling rate since the dead-band excursion is typically no greater than 30 Hz. To compensate for jitter, the FPA sampling rate is typically increased to 10 times² the expected vibration signal (e.g. 2-3 kHz for vibration spectra content to 300 Hz). But, for deep-space applications this requires a high power beacon (i.e. short exposure times) and eliminates the possibility of using other sources for the beacon signal (e.g. stars, extended earth-image). In order to alleviate this difficulty and to enhance the utility of the legacy architecture³, a high bandwidth inertial sensor has been introduced to provide compensation for S/C jitter⁴. Inertial sensors are available that can measure wide-bandwidth signals (up

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The diagram illustrates the effect of platform vibration on optical communication and the resulting residual error for different compensation schemes. It is divided into two main sections: a schematic of the system and a plot of residual error.

Schematic of the System:

- Top Section:** Shows a spacecraft on a platform experiencing "Spacecraft Vibration". An "Optical Comm Platform" is mounted on the spacecraft. A "Deadband Excursion" is indicated by a vertical arrow. The platform is tilted, and the optical beam is shown as a fan of lines.
- Middle Section:** Shows the "Optical Compensation Only" scheme. The platform is tilted, and the optical beam is shown as a single line.
- Bottom Section:** Shows the "Optical + Inertial Sensor Compensation" scheme. The platform is tilted, and the optical beam is shown as a single line.

Residual Error Plot:

- Top Plot:** Shows the "Deadband excursion." and "Jitter excursion due to vibration." The plot shows a large, noisy signal with a significant peak-to-peak excursion.
- Middle Plot:** Shows the "Best case expected residual error with optical only updates at low-moderate update rate." The plot shows a smaller, noisy signal.
- Bottom Plot:** Shows the "Using high bandwidth gyro compensation to reduce the RMS error and worst case effect of platform vibration. Below we see a blowup for the typical gyro/star update drift compensation scheme, where the star updates compensate for the accumulated drift." The plot shows a very small, noisy signal.

This novel enhancement to the single-FPA ATP architecture has numerous advantages. It is independent of range, it can use natural and artificial beacons, it can have a steady reference update rate, and it only requires a single high precision FPA (without requiring a high rate frame transfer). This architecture is shown in Figure 2. Whereas the legacy architecture depended on a single fast control loop, this enhanced architecture utilizes a slow control loop to compensate for known motion and a fast control loop to compensate for high frequency S/C vibration.



Laboratory functional validation of this architecture is presented in this paper utilizing accelerometers to assist in beacon tracking. This is shown by: 1) validation of the algorithms used to estimate displacement, 2) demonstrating that achievable performance meets deep space requirements, 3) tracking beacon under vibration.

2. LABORATORY DEMONSTRATION

The steps completed to achieve inertial-sensor based ATP were algorithm development, theoretical analysis, simulation, lab validation of the algorithm and concept demonstration. In order to demonstrate the concept an accelerometer was integrated into the control loop, the algorithms were implemented into the legacy ATP system, and pointing control was demonstrated using a fast steering mirror (FSM).

Three algorithms were developed. These were the double integration position estimator, acceleration bias estimator, and the initial velocity estimator⁵. The accelerometer scale factor is currently estimated using specific values and offline calibrations. Figure 3a shows a sampled acceleration using the QA-3000 from Allied Signal. The acceleration signal was obtained by mounting the accelerometer on JPL's Vibration Platform Testbed⁶. A piezo-electric linear actuator provides the motion for this testbed. The sampled acceleration was analytically processed to obtain an estimate of the displacement using the three algorithms. Figure 3b compares the estimated displacement to the true value. The true value was obtained using a strain-gauge displacement sensor that is built-in to the linear actuator. Good agreement is obtained thereby validating the algorithms developed.

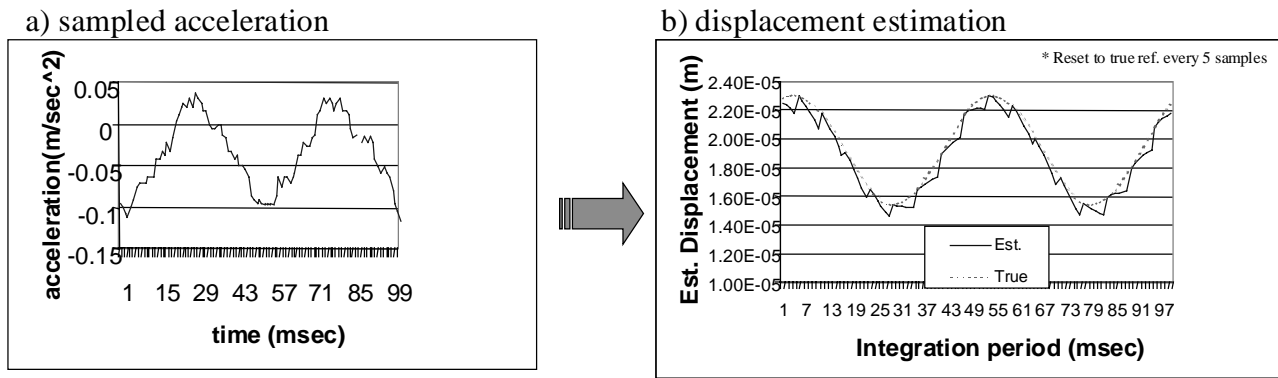


Figure 3a. Sampled acceleration from vibration platform. 3b. Good agreement demonstrated between estimated displacement and true displacement.

Simulation of the performance achievable with accelerometer-assisted tracking is shown in Figure 4. This step was performed in order to confirm that the errors propagated from accelerometer and algorithms were within the allocated budget to meet deep space pointing requirements. For this simulation the noise was taken as a random, one sigma value of $7.6 \mu\text{g}$ from 0-10 Hz and $76 \mu\text{g}$ from 10 to 1000 Hz. The displacement algorithm is based on the trapezoidal rule. A Mars link with less than 1 micro-radian pointing error requires that the displacement estimation error be less than 0.2 microradians [1]. Figure 4 demonstrates the dependence of the displacement error on the integration period and the sampling rate. The error demonstrates a t-squared dependence with integration time. As highlighted in the figure, in order to maintain within the allocated error, the fast control loop (running at 1 kHz) will need to be updated every 43 Hz with the optical tracking reference signal in order to reset for the accumulated drift. Both of these rates are readily achievable with today's technology. By operating the optical reference signal at such low update rates, it allows for long integration times and therefore enables the use of stars and extended earth-image tracking. Increasing the sampling rate of the fast control loop will decrease the accumulated drift⁷, thereby allowing even longer integration times. Furthermore, when beacon signal is stronger, the reference update rate can be increased to reduce the error and thereby provide more margin to the communications link.

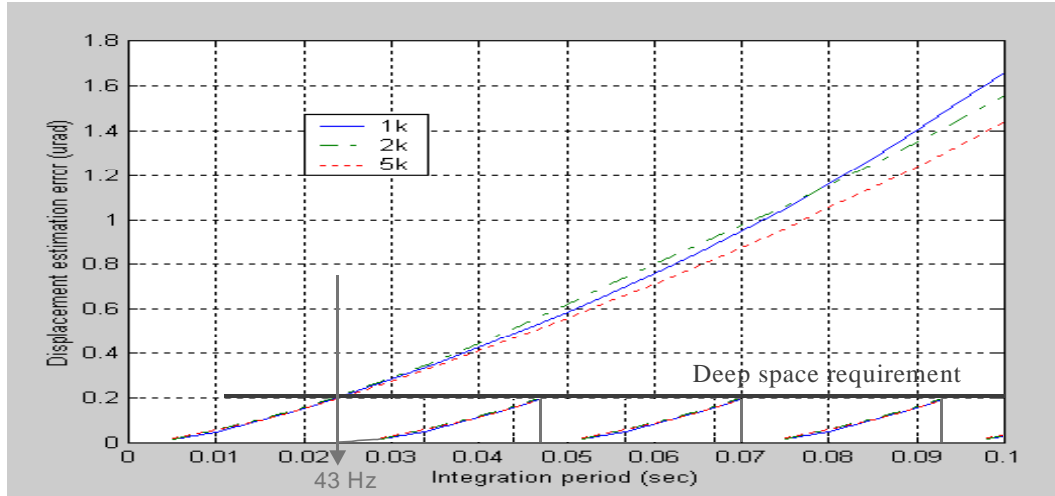


Figure 4. Displacement estimation error dependence on integration period and accelerometer sampling rate.

A simple experiment was performed to validate the algorithms and to gauge the performance achievable with our sampling equipment. The experiment consisted of mounting the accelerometer on the VPT, introducing sinusoidal vibrations at various frequencies, sampling the accelerometer, and having the algorithms compute the estimated displacement. The resulting experimental displacement estimation error is shown in Figure 5 compared to the simulation results. As can be seen very good agreement is obtained. The overall estimation error is larger in this experiment over the simulated results of figure 4. A large component of this increase is believed to be caused by the high level of ambient noise in the laboratory. A base noise of $300 \mu\text{g}$'s was measured which is 5 times larger than the sensitivity of the accelerometer.

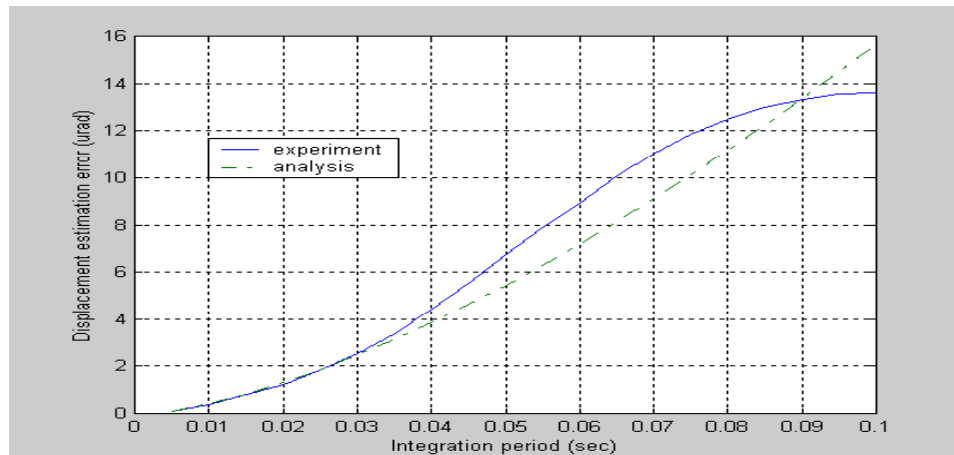


Figure 5. Experimental displacement estimation error.

Accelerometer-assisted beacon tracking was functionally demonstrated using the laboratory set-up depicted in Figure 6. The set-up is comprised of a slow-rate control loop ('optical-tracking') interlaced with a fast-rate control loop ('accelerometer-tracking'). The beacon laser and accelerometer are mounted on the vibration platform driven by the piezo-electric linear actuator. The beacon beam and transmit laser are imaged onto a custom high-rate 128×128 CCD⁸ Dalsa camera. The pointing mechanism is an FO-35 fine-steering mechanism (FSM) from Left-Hand Design Corporation.

In the functional demonstration, the fast-rate control loop samples the accelerometer at a 1 kHz rate, estimates the new position, and updates the command to the FSM. This command to the FSM is interlaced every 5th frame with updates from the slow-rate control loop (optical reference update). This reference is obtained by sampling the CCD (at effectively 200 Hz), computing the centroid of the beacon location and updating the command to the FSM.

The accelerometer-assisted tracking is compared to the case using optical tracking only in Figure 6b under a vibration signal of 45 Hz. It is seen that reducing the optical tracking update rate and ‘assisting’ with accelerometer information (for four intermediate frames) yields very good tracking of the vibrating beacon signal. This same experiment was repeated for various vibration signals. Under the influence of these vibration signals, the results indicate that, on average, the FPA update rate can be reduced by a factor of 5 when maintaining the centroid accuracy to $1/10^{\text{th}}$ pixel. The tracking was very good even with a distorted sinusoid vibration signal (caused by the vibration platform). The transmit and beacon signals show a time delay that is due to integration, centroid computation, image transfer and mirror update existing in the legacy hardware. This has been previously quantified to be 1.5-3 samples⁹, depending on frame rate.

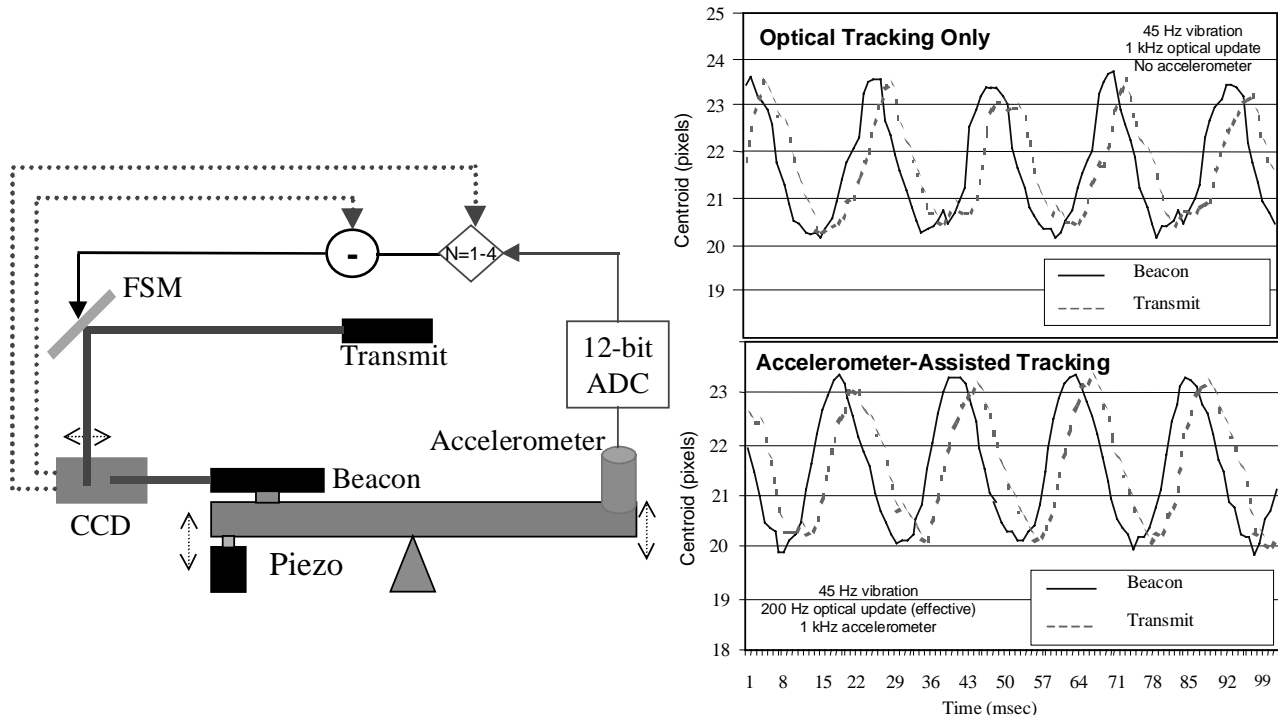


Figure 6a. Experimental set-up used for accelerometer-assisted beacon tracking. 6b. Demonstration of accelerometer-assisted tracking

3. CONCLUSION

Accelerometer-assisted beacon tracking has been demonstrated in the laboratory. By interlacing a fast-rate control loop (based on an inertial sensor) with a slow-rate control loop (optical tracking) a novel architecture has been validated. This architecture presents significant possibilities for deep space optical communications. This architecture is not limited in range because the optical tracking reference can be supplied by laser beacon, star trackers or extended earth-image. It also no longer requires a high-speed FPA for receiver location updates. It inserts an ‘estimator’ to make use of inertial measurements as well as optical measurements. Furthermore, this architecture is capable of removing the intrinsic time delay (image exposure duration) with high bandwidth inertial sensor; it makes the mirror control error independent of optical frame rate; it makes the ATP-system independent of particular sensors; and can still be used in an optical-only system.

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